

## Solar Neutrinos: Expecting 1996 \*

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### Abstract

These are remarks (mainly on the solar neutrinos) written in anticipation of 1996 - the year which can be crucial for the neutrino physics. Recent results on solar neutrinos are discussed. The topics include: (solar) model independent approach to the solar neutrino problem, status of different solutions of the problem, standard and non-standard scenarios of the lepton mixing, light singlet fermions and the neutrino phenomenology.

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# 1 Introduction

According to time schedule [1] in January - March '96 stainless tank placed in the Kamioka mine will be filled by 50.000 tons of water and in April 96 the SuperKamiokande – the detector of new generation of the underground experiments – will start to take data. Later Sudbury detector [2] will to be “on the line”. CHORUS [3] is expected to announce first results. CHOOZ [4] - the first long base line reactor experiment will begin to operate soon.

The results from these experiments may resolve neutrino puzzles we are discussing now. In any case they will have strong impact not only on the neutrino physics and astrophysics but also on particle physics as whole.

Taking this into account it may be wise to abstain from further theoretical speculations and just wait (laying a bet) for new experimental results. On the other hand it is a good time to summarize what we have learned and to understand what is our starting point before new results will arrive. It is a good time to formulate *a priori* criteria according to which we will make the conclusions in future.

## 2 Experiment and Theory

### 2.1 Experiment

1. Results from all solar neutrino experiments [5, 6, 7, 8] are stable. There are small changes of the average signals within  $1\sigma$ : Homestake result has increased by  $1\sigma$  [5], Kamiokande flux decreased by statistical  $1\sigma$  [6], the change of GALLEX result is even smaller [8].

2. The error bars slowly decrease indicating that even Gallium experiments become “old”. When experiments become old it is a proper moment to speak about time variations. Search for time variations is one of justifications to continue the experiments. Recent analysis of Gallium data shows very good agreement with constant original flux and even admission of different time variations practically does not improve the goodness of the fit [8].

Another justification is accuracy. In fact, one can imagine a situation when, even 50% decrease of error bars in Gallium experiment could be decisive for the problem.

Kamiokande does not see any time variations (day-night, seasonal, anticorrelation with solar activity etc..) at least with more than 30% amplitude. Of course, an experienced eye can find about 4 years period “wave” (especially if one removes systematical errors).

During last 5 years Homestake data did not show neither correlations nor anticorrelations with sunspot numbers (and in this sense there is a good agreement with Kamiokande negative result). The confidence level of the anticorrelation during all the period of observation is approximately the same as in 1980 [9]. That is the effects is essentially due to very low signal during one year: 1979 - 1980. This was the year of change of the magnetic field polarity in the Sun. (Accidental coincidence? This can be check in the year 2002). Runs with high counting rate in the period of low activity 1986 - 1987 have rather peculiar statistical distribution [10].

Anyway, SuperKamiokande will continue the Kamiokande job. Iodine experiment can probably substitute Chlorine monitoring, and it will be certainly worthwhile to have Gallium experiment working during the operation of SuperKamiokande and SNO (just in case).

3. It is difficult to overestimate the importance of the result of GALLEX experiment with  $^{51}\text{Cr}$  source [11]. It gives not only the overall check of the solar experiment and especially, the efficiency of detection in the important energy region of the  $^7\text{Be}$  neutrinos. It gives the credit to radiochemical method, and therefore the additional credit to the Homestake result.

4. One more result on the solar neutrinos: recently new bound on the antineutrino flux from the Sun  $\Phi(\bar{\nu}_e)$  has been published by LVD collaboration [12]

$$\Phi(\bar{\nu}_e) = (2 - 4) \cdot 10^{-3} \text{ cm}^{-2} \text{ s}^{-1}, \quad (1)$$

i.e.  $\Phi(\bar{\nu}_e)/\Phi_B^{SSM} = 0.3 - 0.6 \%$ , where  $\Phi_B^{SSM}$  is the boron neutrino flux according to the SSM. The bound has an important implication to the spin-flavor precession of the solar neutrinos.

## 2.2 Theory

Standard Solar Model (SSM) predictions were updated recently in a number of aspects. New values of input parameters like nuclear cross sections, solar age, abundance of the elements, radiative opacities etc.. are used. The uncertainties related to the pre-Main sequence evolution, to the depth of the convection zone etc., were studied (see [15] for review). The most important changes are related to taking in to account the diffusion of heavy elements (C, N, O, ..., Fe, Ni ...). The diffusion leads to increase of the opacity in the radiative zone, and consequently, in increase of the central temperature of the Sun by about 1.1 %. As a result the boron and the beryllium neutrino fluxes increase by 17 % and 6 % correspondingly.

The solution of the  ${}^7\text{Li}$ -problem - one of the origin of doubt in the reliability of the SSM itself and its predictions of the neutrino fluxes - probably has been found. The reason of the Li- deficit (whose surface concentration is about 200 times smaller than expected) could be in plasma physics [16]. It has been pointed out that in the effective screening potential of the electron cloud the nuclei become more transparent to each other. This increases the effective energy of collisions by 600 - 700 eV which leads to decrease of temperature of the  ${}^7\text{Li}$  burning. Also diffusion becomes more efficient.

## 3 Experiment without Theory

### 3.1 Solar neutrino problem without solar model

In spite of serious progress in the solar modelling and very good agreement of SSM and helioseismological data, some predicted solar neutrino fluxes still have rather large uncertainties. Mainly, they are related to the nuclear cross-sections (first of all, for the reaction  $p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma$ ) and probably to some plasma effects which have not yet been properly taken into account [17].

These uncertainties will hardly be fixed before new experiments on solar neutrinos start to operate. In this connection the approach to the problem has been elaborated which does not use the absolute values of neutrino fluxes from the SSM. Main points of the approach which can be called “solar neutrino problem without solar model” are the following [18] - [30]:

1. Only general notion is used about the solar neutrinos: the composition and the energy spectra of components, but not the absolute values of fluxes. These absolute values are considered as *free parameters to be found from the solar neutrino experiments*. In particular, the boron neutrino flux can be represented as

$$\Phi_B = f_B \cdot \Phi_B^{SSM}, \quad (2)$$

where  $f_B$  is free parameter, and  $\Phi_B^{SSM}$  is the flux in the reference SSM e.g. [31]. Similarly, the parameters  $f_i$  ( $i = \text{Be}, pp, NO$ ) for other important fluxes can be introduced.

2. The data from different experiments are confronted immediately.
3. The solar neutrino fluxes are normalized on the solar luminosity (the normalization is based on the condition of thermal equilibrium of the Sun).

Already existing data allow one (i) to formulate the problem in practically model independent way, (ii) to restrict not only neutrino parameters but also original neutrino fluxes. In future precision solar neutrino data will be used to get the information on solar model [28]. Thus we will turn to the original proposal to study the interior of the Sun by neutrinos.

There are two key points in the analysis of present experimental situation.

*Kamiokande versus Homestake* [18] - [26]. Suppose first that neutrino flux consists of  $\nu_e$  only. Then boron neutrino flux measured by Kamiokande gives the contribution to Ar-production rate  $Q_{Ar,B} = 3.00 \pm 0.45$  SNU which exceeds the total signal observed by Homestake:  $Q_{Ar}^{obs} = 2.55 \pm 0.25$  SNU. This means that the contributions of all other fluxes to  $Q_{Ar}$ , and in particular, of Beryllium neutrinos should be strongly suppressed.

*Gallium Experiment Results versus Solar Luminosity* [20, 21, 32, 23]. The luminosity of the Sun allows one to estimate the pp- neutrino flux, and consequently its contribution to Ge-production rate:  $Q_{Ge,pp} \approx 71$  SNU. This value plus small ( $\sim 5$  SNU) contribution of boron neutrinos coincides with total signal observed by GALLEX. Consequently, gallium results can be reproduced if the beryllium neutrino flux as well as all other fluxes of the intermediate energies are strongly suppressed.

Thus both these points indicate on strong suppression of the  ${}^7\text{Be}$ - neutrino flux (if there is no neutrino conversion). Statistical analysis gives  $f_{Be} < 0.3$  ( $2\sigma$ ) (for more detail see [25, 26]).

The solar neutrino problem becomes more detailed. It can be formulated as

1. Deficit of boron neutrinos
2. Deficit of the beryllium neutrinos.

The first one is strongly model dependent. In fact, it may have the astrophysical or/and nuclear physics explanation: say, 25% decrease of the  $S_{17}$  and 1% decrease of the central temperature (due to the plasma effects) are enough to accommodate the Kamiokande result. The second deficit is essentially (solar) model independent and it is almost impossible to explain it by reasonable variations of parameters.

### 3.2 Best fit of the data

If nothing happens with neutrinos and the flux at the Earth consists of the electron neutrinos, then the data fix uniquely values of fluxes which give the *best fit* [29]:

1. Boron neutrino flux should be  $\approx (0.35 - 0.40)\Phi_B^{SSM}$ .
2. Beryllium neutrino flux as well as other fluxes of the intermediate energies (pep, N, O) give negligible contributions to the signals.
3. There is little or no suppression of the pp-flux.

Thus the energy dependence of the suppression factor  $P(E)$  can be represented as

$$\begin{aligned}
 P(E < 0.5 \text{ MeV}) &\equiv P_{pp} = 0.9 - 1, & P(E = 0.7 - 1.5 \text{ MeV}) &\equiv P_{Be} \sim 0, \\
 P(E > 7 \text{ MeV}) &\equiv P_B = 0.4 - 1.
 \end{aligned}
 \tag{3}$$

Large uncertainty of suppression in high energy region is related to the uncertainty in the original boron neutrino flux. Kamiokande admits a mild distortion of the recoil electron spectrum.

Evidently the astrophysics can not reproduce such a picture [18, 19], [21] - [26]. Typically one gets more strong suppression of the boron neutrino flux than the beryllium neutrino flux.

(To reproduce central values of signals one should suggest that there is an additional flux which contributes to the Kamiokande signal,  $\Delta\Phi_B \approx 0.09\Phi_B^{SSM}$ , but does not contribute to the Ar-production rate. This however implies the conversion of the electron neutrinos to muon or tau neutrinos).

The suppression profile can be strongly changed if one admits the existence of muon or/and tau neutrino components in the solar neutrino flux (which already implies some kind of neutrino transformations). In this case, especially if the original boron neutrino flux is higher than in SSM,  $\nu_\mu$  and  $\nu_\tau$  scattering on electrons can give big (main) contribution to the Kamiokande result and the statement that beryllium neutrino flux should be strongly suppressed is not true. Denoting by  $P_{Be}$  the suppression factor in the region of Be-neutrinos (at the intermediate energies) we find the suppression factor for the boron neutrinos needed to reproduce the Homestake result:

$$P_B = \frac{Q_{Ar}^{obs} - P_{Be}Q_{Ar,int}^{SSM}}{f_B Q_{Ar,B}^{SSM}}, \quad (4)$$

where  $Q_{Ar}^{obs}$  is the measured Ar-production rate,  $Q_{Ar,int}^{SSM}$  and  $Q_{Ar,B}^{SSM}$  are respectively the contributions of fluxes of intermediate energies (Be, pep, N, O) and the boron neutrino flux to the Ar-production rate according to the reference SSM [31]. The original boron neutrino flux which is needed to reproduce the Kamiokande signal can be found from condition  $R_{\nu e} = f_B[P_B + (1 - P_B)/6]$ , where  $R_{\nu e} \equiv \Phi_B^{obs}/\Phi_B^{SSM}$  is the suppression factor observed by Kamiokande. Substituting  $P_B$  from (4) in this condition one gets

$$f_B \approx 6R_{\nu e} - 5 \frac{Q_{Ar}^{obs}}{Q_{Ar,B}^{SSM}} + P_{Be} \frac{Q_{Ar,int}^{SSM}}{Q_{Ar,B}^{SSM}}. \quad (5)$$

Then predicted values of  $Q$  [31] and the central values of experimental signals give according to (5)  $f_B \approx 1.4$  for  $P_{Be} = 0.5$  and  $f_B \approx 2.1$  for  $P_{Be} = 1$ . That is to avoid any suppression of the Be-neutrino flux one needs two times larger original boron neutrino flux. For  $2\sigma$  smaller value of  $R_{\nu e}$  and  $f_B = 1$  the suppression as weak as  $P_{Be} \sim 0.7$  becomes allowed. Thus if neutrinos undergo conversion, the Be-neutrino flux may not be suppressed.

In the case of weak suppression of the beryllium line the pp-neutrino flux should be suppressed according to the Gallium result:

$$P_{pp} = \frac{1}{Q_{Ge,pp}^{SSM}} \left[ Q_{Ge}^{obs} - P_{Be}Q_{Ge,int}^{SSM} - P_B f_B Q_{Ge,B}^{SSM} \right], \quad (6)$$

where  $Q_{Ge,pp}^{SSM}$  and  $Q_{Ge,int}^{SSM}$  are predicted contributions to the Ge-production rate from pp - flux and the intermediate energy fluxes. For  $P_{Be} \sim 0.7$  one gets from (6)  $P_{pp} \sim 0.6$ .

Such a situation (weak suppression of the beryllium flux and appreciable suppression of the pp-flux) is realized e.g. in the case of vacuum oscillations [36].

## 4 Neutrino parameters and neutrino fluxes

Although the solar neutrino problem can be formulated in practically model independent way the implications to the neutrino physics strongly depend on the original fluxes. There are several recent studies of the particle physics solutions of the solar neutrino problem according to the (solar) model independent approach [27, 29, 30, 33, 34, 35].

### 4.1 Long length vacuum oscillations

These oscillations can reasonably well reproduce the desired suppression. For  $\Delta m^2 > 3 \cdot 10^{-11}$  eV<sup>2</sup> the pp-neutrino flux is in the region of averaged oscillations, where  $P = 1 - 0.5 \sin^2 2\theta$ , the Beryllium neutrinos are in the fastly oscillating part of the  $P(E)$  (so that one expects an appreciable time variations of the Be-neutrino flux due to annual change of distance between the Sun and the Earth). Boron neutrinos are in the first (high energy) minimum of  $P(E)$ . This allows one to reach the inequality  $P_{pp} > P_B > B_{Be}$  implied by (3). However, there is an obvious relation between maximal suppression of the Be-line and suppression of pp-neutrinos:  $P_{Be,min} = 2P_{pp} - 1$ , and due to this the best fit configuration (3) is not realized. Good fit can be obtained for moderate suppression of the Be-line and  $\sim 0.6$  suppression of the pp-neutrinos. The fit becomes better for increased values of  $f_B$  [33].

With diminishing  $f_B$  the needed suppression of B-neutrino flux due to the oscillations becomes weaker. Therefore for fixed values of  $\Delta m^2$  the allowed regions of parameters shift to smaller  $\sin^2 2\theta$  [33, 34]. In particular, for  $f_B = 0.7$ , the region is at  $\sin^2 2\theta < 0.7$  thus satisfying the bound from SN87A [37]. For  $f_B \sim 0.4$  mixing can be as small as  $\sin^2 2\theta < 0.5 - 0.6$ . Moreover, for  $f_B = 0.5$  the allowed region appears at  $\Delta m^2 \sim 5 \cdot 10^{-12}$  eV<sup>2</sup> which corresponds to the Be-neutrino line in the first high energy minimum of  $P$ , pp-neutrinos in the first maximum of the  $P$  and high energy part of the boron neutrino spectrum out of suppression pit. No appreciable time variations are expected. Such a configuration is quite similar to that of very small mixing MSW solution which further increases the ambiguity of situation. Distortion of pp-neutrino spectrum is the signature of the solution [35].

Depending on neutrino parameters and  $f_B, f_{Be} \dots$  one can get variety of distortions of the boron neutrino energy spectrum [34].

Being excluded at  $f_B = 1$ , the oscillations into sterile neutrino are allowed for  $f_B < 0.7$  [35].

### 4.2 Resonance flavor conversion

It can precisely reproduce the desired energy dependence of the suppression factor (3). In the region of small mixing angles one has

$$P_{pp} \sim 1, \quad P_{Be} \sim 0, \quad P_B \sim \exp(-E_{na}/E), \quad (7)$$

where  $E_{na} \equiv \Delta m^2 l_n \sin^2 2\theta$ . Additional contribution to Kamiokande  $\Delta f_B \approx 0.09$ , follows from scattering of the converted  $\nu_\mu$  ( $\nu_\tau$ ) on electrons due to the neutral currents. With diminishing  $f_B$  the suppression due to conversion should be relaxed, and therefore  $\sin^2 2\theta$  should decrease according to (7) [29, 30]. At  $\Delta m^2 = 6 \cdot 10^{-6}$  eV<sup>2</sup> the best fit of the data for flavor mixing corresponds to the pairs of parameters [29]:  $(f_B, \sin^2 2\theta) = (0.4, 1.0 \cdot 10^{-3}), (0.75, 4.3 \cdot 10^{-3}), (1.0, 6.2 \cdot 10^{-3}), (1.5, 9 \cdot 10^{-3}), (2.0, 10^{-2})$ . The decrease of  $f_{Be}$  gives an additional small shift

of the allowed region to smaller values of  $\sin^2 2\theta$ . A consistent description of the data has been found for [29]

$$f_B \sim 0.4 - 2.0.$$

For unfixed values of the original fluxes,  $f_B, f_{Be} \dots$ , the allowed region of neutrino parameters is controlled immediately by Gallium data and by the “double ratio”. Namely, the mass squared difference

$$\Delta m^2 = (6 \pm 4) \cdot 10^{-6} \text{eV}^2, \quad (8)$$

is restricted by Gallium results which imply that the adiabatic edge of the suppression pit is in between the end point of the pp-neutrino spectrum and the Be-line. This bound does not depend on mixing angle in a wide region of  $\theta$ . (For sterile neutrinos the bound is approximately the same). For fixed  $\Delta m^2$  the mixing  $\sin^2 2\theta$  is determined by the “double ratio”

$$R_{H/K} \equiv \frac{R_{Ar}}{R_{\nu e}},$$

where  $R_{Ar} \equiv Q_{Ar}^{obs}/Q_{Ar}^{SSM}$  is the suppressions of signals in *Cl-Ar* experiment and  $Q_{Ar}^{SSM}$  is the predictions in the reference model [31]. The experimental value,  $R_{H/K} = 0.65 \pm 0.11$ , admits  $\sin^2 2\theta = 1.0 \cdot 10^{-3} - 1.5 \cdot 10^{-2}$ . Similar bound exists for the conversion to sterile neutrinos if one restricts the original boron neutrino flux by  $\Phi_B \leq 1.5 \Phi_B^{SSM}$ .

For very small mixing solution:  $f_B \sim 0.5$ ,  $\sin^2 2\theta_{es} \sim 10^{-3}$ , all the effects of conversion in the high energy part of the boron neutrino spectrum ( $E > 5 - 6$  MeV) become very weak. In particular, the distortion of the energy spectrum disappears, and the ratio charged-to-neutral currents  $(CC/NC)^{exp}/(CC/NC)^{th}$  approaches 1. Thus studying just this part of spectrum it will be difficult to identify the solution (e.g., to distinguish the conversion and the astrophysical effects). Recent calculations in SSM with diffusion of heavy elements give larger boron neutrino flux [13, 15], so that even with 25% decrease of nuclear cross-section and 1% decrease of central temperature of the Sun one still needs an appreciable conversion effect. This gives a hope that the problem can be resolved by SuperKamiokande/SNO experiments.

With increase of  $f_B$  the fit of the data in the large mixing domain becomes better [29]. Here the Kamiokande signal can be explained essentially by NC effect and mixing can be relatively small. Be- neutrino flux is sufficiently suppressed and suppression of the pp-neutrinos is rather weak. For  $f_B = 2$  the values  $\sin^2 2\theta = 0.2 - 0.3$  become allowed. Corresponding mass squared difference is  $\Delta m^2 = 6 \cdot 10^{-6} - 10^{-4} \text{eV}^2$ .

### 4.3 The effect of third neutrino

The analysis of data in terms of two neutrino mixing is quite realistic, since in the most interesting cases (simultaneous solution of the solar and hot dark matter problems, or solar and atmospheric neutrino problems) third neutrino has large mass so that its  $\Delta m^2$  is beyond the resonance triangle and its mixing to the electron neutrino is rather small. This reduces the three neutrino task to the case of two neutrino mixing. However, there is one interesting example where third neutrino could influence the solutions of the solar neutrino problem. It was considered previously [38, 39, 40] and reanalyzed recently in [41]: The third neutrino is in the region

of the solution of the atmospheric neutrino problem:  $m_3 \sim 0.1$  eV and it has an appreciable admixture to the electron neutrino state. Let us represent the  $\nu_e$  as

$$\nu_e = \cos \phi \nu' + \sin \phi \nu_3 \quad (9)$$

where

$$\nu' = \cos \theta \nu_1 + \sin \theta \nu_2$$

and  $\phi$  is not small. In the case  $m_3 \gg m_2$  the third neutrino  $\nu_3$  “decouples” from the system (as far as we deal with the Sun) and its effect is reduced just to the averaged vacuum oscillations. In turn  $\nu'$  converts resonantly to its orthogonal state. So that the survival probability can be written as [39]

$$P = \cos^4 \phi P_2 + \sin^4 \phi, \quad (10)$$

where  $P_2$  is two neutrino survival probability. Additional regions of the neutrino parameters  $\Delta m^2 = (10^{-5} - 10^{-6})$  eV<sup>2</sup> and  $\sin^2 2\theta = 3 \cdot 10^{-4} - 3 \cdot 10^{-3}$  are allowed for  $\cos^4 \phi \sim 0.5 - 0.7$ . Now both pp- and Be- neutrinos can be outside the  $2\nu$  - suppression pit [39], where  $P_2 \approx 1$  and according to (10) the suppression factor for them is  $(\cos^4 \phi + \sin^4 \phi)$ . This allows one to get about 1/2 suppression of the gallium production rate, and reconcile the Homestake and the Kamiokande results at  $2\sigma$  level. In [41] it is claimed that even the adiabatic solution (when the high energy part of the boron neutrino spectrum is on the adiabatic edge) is not excluded. Indeed, now the distortion of the boron neutrino spectrum is weakened by factor  $\cos^4 \phi$  in comparison with two neutrino case. But even this is disfavored by the data. Large mixing with electron neutrinos (now  $\sin^2 2\phi \sim 0.75$ ) is practically excluded by reactor experiment [42] and CHOOZ will finally check this possibility.

#### 4.4 On the spin-flip effects

Resonance spin-flip precession can precisely reproduce the suppression profile [43, 44, 45], i.e. give very good description of averaged signals.

For values of the magnetic moment at the upper bound:  $\mu \sim 3 \cdot 10^{-12} \mu_B$ , where  $\mu_B$  is the Bohr magneton, the strength of the magnetic field as big as  $10^6$  Gauss is needed. Traditional objection is that this field is much stronger than usually expected one. There is another objection. In the most of calculations it was suggested that there is no *latitude* dependence of the field which is certainly incorrect: the toroidal field has different polarity in the southern and northern semispheres and there is the equatorial gap of the field. One can think that existing calculations correspond to some average field. However this means that there are regions with even stronger field than that mentioned above. Moreover, since the spin-flip effect is non-linear in the field one should calculate first the probabilities for different latitudes and then perform the averaging over the latitude rather than use the average field. In fact, it was shown [45] that for reasonable latitude distributions of the field the average suppression is too weak, moreover one expects an appreciable seasonal effect.

Time variations of signals are generic features of this solution. Where are these variations?

## 5 Standard and non-standard

The solution of the solar neutrino problem can be reconciled with solutions of (all ?) other neutrino anomalies like deficit of the atmospheric  $\nu_\mu$ - flux, possible signal of the  $\bar{\nu}_\mu - \bar{\nu}_\tau$  oscillations, existence of hot component of dark matter. A number of schemes of the neutrino masses and



mixing has been suggested in this context. Thinking in term “standard” and “non-standard” one can arrive at the following (at least the most popular) scenario.

### 5.1 “Standard” scenario of neutrino masses and mixing

- (i). Neutrino masses are generated by the see-saw mechanism with masses of the RH components  $M_R = 10^{11} - 10^{13}$  GeV. The mass scale  $10^{13}$  GeV can originate, e.g., from Grand Unification scale,  $M_{GU}$ , and the Planck scale,  $M_P$ , as  $M_R \sim M_{GU}^2/M_P$ .
- (ii) Second mass,  $m_2$ , is in the range

$$m_2 = (2 - 3) \cdot 10^{-3} \text{eV}, \quad (11)$$

so that the resonance flavor conversion  $\nu_e \rightarrow \nu_\mu$  solves the solar neutrino problem. The desired mixing angle is consistent with

$$\theta_{e\mu} = \sqrt{\frac{m_e}{m_\mu}} - e^{i\phi}\theta_\nu, \quad (12)$$

where  $\theta_\nu$  comes from diagonalization of neutrino mass matrix. This relation is similar to corresponding relation in quark sector which testifies for certain quark-lepton symmetry (unification).

- (iii) The third neutrino (for  $m^D \sim 100$  GeV and  $M \sim 3 \cdot 10^{12}$  GeV) has the mass about 5 eV. It composes the desired hot component of the dark matter.

- (iv) The decays of the RH neutrinos with mass  $10^{12}$  GeV can produce the lepton asymmetry of the Universe which can be transformed by sphalerons in to the baryon asymmetry [46].

- (v) Large Yukawa coupling of neutrino from the third generation, e.g.  $Y_\nu \sim Y_{top}$ , gives appreciable renormalization effects in the region of momenta  $M_R - M_{GU}$ . In particular, the  $b - \tau$  mass ratio increases by (10 – 15)% in the MSSM. In turn this disfavors the  $b - \tau$  mass unification for low values of  $\tan\beta$  [47].

- (vi) Simplest schemes with quark - lepton symmetry lead to mixing angle for the  $e$  and  $\tau$  generations:  $\theta_{e\tau} \sim (0.3 - 3)V_{td}$  which is close to the bound from the nucleosynthesis of heavy elements (r-processes) in the inner parts of the supernovae:  $\sin^2 2\theta_{e\tau} < 10^{-5}$  ( $m_3 > 2$  eV) [48].

- (vii) For  $\mu - \tau$  mixing one expects [49]  $\theta_{\mu\tau} \sim kV_{cb}\eta$ , where  $k = 1/3 - 3$  and  $\eta \sim 0.6 - 0.7$  is the renormalization factor. If  $m_3 > 3$  eV some part of expected region of mixing angles is already excluded by FNAL 531. Large part of the region can be studied by CHORUS and NOMAD. The rest (especially  $m_3 < 2$  eV) could be covered by E 803.

- (viii) The depth of  $\bar{\nu}_\mu - \bar{\nu}_e$  oscillations with  $\Delta m^2 \approx m_3^2$  equals  $4|U_{3\mu}|^2|U_{3e}|^2 \approx 4|\theta_{e\tau}|^2|\theta_{\mu\tau}|^2$ . The existing experimental bounds on  $\theta_{e\tau}$  and  $\theta_{\mu\tau}$  give the upper bound on this depth:  $< 10^{-3}$  [50] which is too small to explain the LSND result.

The standard scenario does not solve the atmospheric neutrino problem. One can consider the scheme with three degenerate neutrinos or sacrifice the HDM suggesting that some other particles are responsible for the structure formation in the Universe. In the latter case  $m_3 \sim 0.1$  eV and strong  $\mu - \tau$  mixing explain via  $\nu_\mu - \nu_\tau$  oscillations the atmospheric neutrino deficit. Strong  $\mu - \tau$  mixing, could be related to relatively small mass splitting between  $m_2$  and  $m_3$  which implies the enhancement of the mixing in the neutrino Dirac mass matrix [51]. It could be related to the see-saw enhancement mechanism [52, 53] endowed by renormalization group enhancement [53] or with strong mixing in the charge lepton sector [54].

## 5.2 More neutrino states?

Safe way to accommodate all the anomalies is to introduce new neutrino state. As follows from LEP bound on the number of neutrino species this state should be sterile (singlet of standard group). Taking into account also strong bound on parameters of oscillations into sterile neutrino from Primordial Nucleosynthesis one can write the following “scenario” [55] – [64].

- (i) Sterile neutrino has the mass  $m_S \sim (2 - 3) \cdot 10^{-3}$  eV and mixes with  $\nu_e$ , so that the resonance conversion  $\nu_e - \nu_s$  solves the solar neutrino problem;
- (ii) Masses of  $\nu_\mu$  and  $\nu_\tau$  are in the range 2 - 3 eV, they supply the hot component of the DM;
- (iii)  $\nu_\mu$  and  $\nu_\tau$  form the pseudo Dirac neutrino with large (maximal) mixing and the oscillations  $\nu_\mu - \nu_\tau$  explain the atmospheric neutrino problem;
- (iv)  $\nu_e$  is very light:  $m_1 < 2 \cdot 10^{-3}$  eV. The  $\bar{\nu}_\mu - \bar{\nu}_e$  mixing can be strong enough to explain the LSND result.
- (v) However production of heavy elements in supernova via “r-processes” is problematic for this scenario.

Sterile neutrino can be used to explain the atmospheric neutrino problem in the context of standard scenario, if one ignores the Nucleosynthesis bound.

## 5.3 Sterile neutrino or light singlet fermion?

Introducing sterile neutrino  $S$  one encounters several questions:

- What is the origin of this neutrino?
- How it mixes with usual neutrinos?
- How one can explain its small mass?

1. *Origin.* Natural candidate is if course, the RH neutrino component. However in this case the see-saw mechanism does not operate. Then  $S$  could be the component of the multiplet of extended gauge symmetry - like  $SO(10)$ - singlet from 27-plet of  $E_6$  [60]. In [61] it was suggested that  $S$  is the mirror neutrino from mirror standard model. In all these cases one has three singlet fermions.

Let us consider another possibility [62, 63]:

- (i).  $S$  has an origin beyond usual fermionic structure, and in particular, beyond the see-saw mechanism. So that the see-saw explains the lightness of the active neutrinos in the usual way.
- (ii).  $S$  has no generation structure and probably is generation blind. There is only one light singlet fermion (although this is not necessarily).
- (iii). Supersymmetry may be a natural framework of the appearance of such a fermion. A number of singlet superfields was introduced for different purposes: to generate  $\mu$  term, to realize PQ-symmetry breaking, to break spontaneously lepton number, etc.. String theory typically supplies some singlets. Fermionic components of these superfield could be identified with desired sterile neutrino.

2. *Mixing.* The standard see-saw structure

$$hL\nu^c H_2 + M\nu^c \nu^c \quad (13)$$

involves three fields: doublet neutrino, RH neutrino component,  $\nu^c$ , and Higgs doublet,  $H_2$ . Correspondingly, there are three possible ways to mix  $S$  with active neutrinos:

(i) via direct coupling to the left handed neutrinos:

$$\epsilon LSH_2. \quad (14)$$

The parameter  $\epsilon$  is of the order

$$\epsilon \sim \frac{m_{3/2}}{M_P}, \quad (15)$$

where  $M_P$  is the Planck mass. This means that  $S$  could be the field from hidden sector which is mixed with usual neutrinos via gravitational interactions.

(ii). mixing via interactions with RH neutrinos:

$$\lambda \nu^c S y, \quad (16)$$

where  $y$  is an additional singlet field which acquires the VEV  $\langle y \rangle \sim m_{3/2}$  as the result of SUSY breaking. The interactions (13) and (16) allow one to explain simultaneously both the mixing of  $S$  with neutrinos and the desired mass of  $S$  without introduction of new mass scales [62, 64].

(iii). mixing via Higgsino:

$$\frac{\mu}{\langle S \rangle} H_1 H_2 S + \epsilon' L H_2. \quad (17)$$

The first term which mixes  $S$  with Higgsino can be responsible also for generation of the  $\mu$ -term. Second term mixes Higgsino with neutrino thus breaking  $R$ -parity. It can be generated spontaneously by the interaction (13), if sneutrino acquires non-zero VEV, or explicitly by, e.g., gravitational interactions.

3. *Mass.* Spontaneous violation of global symmetry, ( $U(1)_G$  in the simplest case) like Peccei-Quinn or lepton number symmetries or horizontal symmetry leads to appearance of the massless boson. In the limit of exact supersymmetry the fermion partner is also massless. However, violation of supersymmetry results in generation of mass of  $S$ . In supergravity one has typically  $m_S \sim m_{3/2}$ . The mass  $m_S$  can be further suppressed by special choice of (i) the superpotential or (ii) Kähler potential. In the first case it is quite easy to get  $m_S \sim m_{3/2}^2/M_G$  which leads to desired value of  $m_S$  for  $M_G \sim 10^{16}$  GeV [63].

Using non-minimal kinetic terms one can suppress  $m_S$  at tree level, one loop or even two loops. In the case of strict no-scale supergravity the mass is generated in three loops which is sufficient to explain the smallness of  $m_S$  for rather natural values of parameters [63].

Another possibility [62] is to use  $R$ -symmetry to protect the mass, to forbid undesired mixing of  $S$  and to ensure that  $S$  does not acquire a VEV. (In this case  $R$ -parity can be conserved). For more details see [65].

Thus discovery of solar neutrinos conversion into sterile neutrinos (and future experiments will be able to do this) may give the hint to supersymmetry and to really very rich physics beyond the standard model.

## 6 Conclusion

Before Gallium experiments we had the following criteria: The counting rate much below 70 - 75 SNU is the proof of new neutrino physics (oscillations, conversion etc.). The counting rate much bigger 75 SNU testifies for astrophysical solution. Nature has chosen precisely 75 SNU,

and has stayed us in uncertain situation for more than 5 years. Although present rather precise data strongly indicate new physics we have not passed through simple *a priori* criteria.

Now we have new chance. *A priori* criteria are: distortion of the energy spectrum of boron neutrinos, anomalous ratio of charged to neutral current number events, day-night effect, seasonal variations...

Following previous logic of Nature one can imagine that neither distortion nor time variations or CC/NC anomaly will be observed. By the way, this is quite possible situation, e.g. if the original boron neutrino flux is small, and the transitions of this flux is not needed. Is this the proof of Astrophysical solution? For boron neutrinos - Yes. Then to explain other experiments one should suggest strong suppression of the Beryllium neutrino flux. This is realized, e.g., in very small mixing MSW - solution. To proof this one should wait again - wait for experiments which are sensitive to beryllium neutrinos and in this case BOREXINO results can be decisive...

Will Nature again play with us? Let us see what will happen ...

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